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OPTIMUM ELEMENT DISTRIBUTION FOR CIRCULAR ADAPTIVE ANTENNA SYSTEMS

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14. ABSTRACT
The performance of circular, planar adaptive antennas is studied. The individual antenna elements are biconical antennas and the weights are adapted using space-only processing or space-time adaptive processing. Various distributions of antenna elements are investigated where the antenna elements are distributed over the whole aperture or just on the perimeter of the circle. It is shown that when all the elements are distributed on the perimeter of the circle, one obtains the best performance.

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Abstract

The performance of circular, planar adaptive antennas is studied. The individual antenna elements are biconical antennas and the weights are adapted using space-only processing or space-time adaptive processing. Various distributions of antenna elements are investigated where the antenna elements are distributed over the whole aperture or just on the perimeter of the circle. It is shown that when all the elements are distributed on the perimeter of the circle, one obtains the best performance.

Keywords: Adaptive antennas, element distribution, circular aperture.

I. Introduction

Adaptive antenna arrays are commonly used in radar and communication systems to suppress radio frequency interference which could be intentional or unintentional. These antennas can steer spatial nulls along narrow band as well as wide band interfering signal directions and can still receive the signal of interest (desired signal). One good example is GPS anti-jam systems. The performance of adaptive antennas strongly depends on the element distribution [1-5]. This is especially true when the number of interfering signals approaches the number of antenna elements; i.e., the adaptive antenna is stressed. In this paper, the performance of a planar circular array of half a wavelength radius is studied. The array consists of seven biconical antennas. Different distributions of antenna elements are investigated where the antenna elements are distributed over the whole aperture or just on the perimeter of the circle. The weights are adapted using space-only processing as well as space-time adaptive processing (STAP). Average output signal-to-interference plus noise ratio (SINR) over the angular region of interest as well as the percentage angular region over which the output SINR is higher than a given threshold for many independent trials are used as the performance metrics. It is shown that for the best performance the antenna elements should be distributed on the perimeter of the circle. This is true for space-only processing as well as for STAP. Also, as expected, STAP performs better than space-only processing.

The rest of the paper is organized as follows. A brief overview of STAP based adaptive antennas is given in the next section where analytical expressions for the adaptive antenna weights and the output SINR are also included. Note that space-only processing is a special case of STAP where a single tap is used behind each antenna element. Element distributions and the incident signal scenarios used in this study are described in Section III. Section IV discusses the performance obtained using space-only processing; whereas Section V contains the performance of STAP. Finally Section VI contains a summary and some general conclusions of this research.

II. STAP Based Antenna Electronics

Figure 1 shows a block diagram of a STAP based adaptive antenna. Note that behind each antenna element there are N taps. T_0 is the delay between various taps. In digital implementation of STAP, T_0 is equal to 1/sampling rate. In the figure, the signals

at various taps are multiplied by some weight and the weighted signals are summed together to form the array output which is given by

$$y(t) = \sum_{l=1}^{L} \sum_{n=1}^{N} x_{ln}(t)\, w_{ln} \tag{1}$$

where $x_{ln}(t)$ is the signal at the n^{th} tap of the l^{th} element, w_{ln} is the corresponding weight, N is the number of taps and L is the number of antenna elements. Using vector notation, (1) can be written as

$$y(t) = \mathbf{x}^T \mathbf{w} \tag{2}$$

where

$$\mathbf{x}^T = \left(x_{11}(t), x_{12}(t), \cdots x_{1N}(t), x_{21}(t), \cdots x_{LN}(t)\right) \tag{3}$$

and

$$\mathbf{w}^T = \left(w_{11}, w_{12}, \cdots w_{1N}, w_{21}, \cdots w_{LN}\right). \tag{4}$$

Next the expected power at the array output is

$$P = \frac{1}{2} E\left\{y^*(t)\, y(t)\right\} \tag{5}$$

$$= \frac{1}{2} \mathbf{w}^H E\left\{\mathbf{x}^*(t)\, \mathbf{x}^T(t)\right\} \mathbf{w} \tag{6}$$

where E{...} is the expectation operator. Note that in (5) we have assumed analytical representation for the incident signals. (6) can be further written as

$$P = \frac{1}{2} \mathbf{w}^H \mathbf{R} \mathbf{w} \tag{7}$$

where $\mathbf{R}$ is a covariance matrix representing the correlation between various signals (including noise) at various taps of the adaptive antenna. Assuming that the various signals incident on the antenna array are uncorrelated with each other and with the thermal noise, the covariance matrix $\mathbf{R}$ can be written as

$$\mathbf{R} = \mathbf{R}_d + \mathbf{R}_i + \mathbf{R}_n \tag{8}$$

where $\mathbf{R}_d$ is the desired signal covariance matrix, $\mathbf{R}_n$ is the noise covariance matrix and $\mathbf{R}_i$ is the covariance matrix for interfering signals. For multiple interfering signals, $\mathbf{R}_i$ can be obtained by summing the covariance matrices for individual interfering signals. Using (7) and (8), the signal-to-interference ratio (SINR) at the array output is

$$\text{SINR} = \frac{\mathbf{w}^H \mathbf{R}_d \mathbf{w}}{\mathbf{w}^H \left(\mathbf{R}_n + \mathbf{R}_i\right) \mathbf{w}} \tag{9}$$

In adaptive antenna arrays, the weight vector is not fixed. The array weights are adapted to the incident signals. In this study, the antenna weights are adapted for beam forming/null steering; i.e., the antenna array output is minimized subject to the constraint

$$\mathbf{s}^H \mathbf{w} = 1 \tag{10}$$

where $\mathbf{s}$ is the steering vector needed to form a beam along the desired signal direction. One needs the antenna array manifold in the desired signal direction for proper beam forming. The adapted weights are then given by [6]

$$\mathbf{w} = \frac{\mathbf{R}^{-1}\mathbf{s}}{\mathbf{s}^H \mathbf{R}^{-1} \mathbf{s}}. \tag{11}$$

III. Element Distribution and Signal Scenario

In this study, the antenna elements are assumed to be distributed on a circular planar aperture of half a wavelength radius. The array consists of seven biconical antennas. Individual elements are oriented perpendicular to the plane of the antenna array. Four different (A1, A2, A3 and A4) distributions of antenna elements as shown in Figure 2 are considered in this paper though many other distributions were investigated. Note that element distribution A1 has one element at the center of the circle and the other six elements are distributed on two concentric circles. Element distribution A2 has one element at the center of the circle and the other six elements uniformly distributed on the perimeter of the aperture. Element distribution A3 has one element at the center of the circle and the other six elements non-uniformly distributed on the perimeter of the aperture. Element distribution A4 has all seven antenna elements distributed on the perimeter of the aperture.

We used a method of moment solution [7] to compute the signal received at the terminals of various elements of the antenna arrays when a signal is incident from any direction in the plane of the antenna array. These calculations were performed to cover the bandwidth of the incident signals in small frequency steps. The calculated antenna responses (manifold) are used in adaptive antenna analysis. Note that the antenna responses include mutual coupling between the antenna elements.

A single desired signal and multiple interfering signals are incident on the antenna array. The angle of arrival of the incident signals is in the plane of the antenna array. The angle of arrival of the desired signal is varied to scan the whole plane. Signal-to-noise ratio of the desired signal on an isolated biconical antenna is 0 dB. All the incident signals are assumed to be uncorrelated with each other and thermal noise in various RF channels. Each interfering signal has 40 dB interference-to-noise ratio (INR) on an isolated biconical antenna. For a given number of incident interfering signals, twenty five independent trials are carried out. The interference angle of arrival is varied randomly from one trial to the next. The average (averaged over twenty five trials) output SINR in the signal direction and the percentage angular region over which the output SINR exceeds a given threshold level are used as the performance metrics. As mentioned earlier, the performance of the antenna array with space-only processing as well as STAP is studied. Performance with the space-only processing is discussed first.

III. Space-Only Processing

Figure 3 shows the output SINR of the four antenna arrays in the absence of all interference signals versus the angle of arrival (AoA) of the desired signal when the desired signal is a CW signal. Note that overall performance of the four antenna arrays is quite similar and is quite good for all AoA of the desired signal. Thus, in the absence of interfering signals, all four antenna arrays would perform well.

Figure 4 shows the average output SINR of the four antenna arrays in the presence of three to six interfering signals. All the incident signals are CW signals. All other parameters are the same as in Figure 3. Note that, as expected, the output SINR degrades in the presence of the interfering signals. The more the number of interfering signals the more is the degradation. Antenna array A4 suffers the least degradation

whereas the antenna array A2 suffers the most degradation. Antenna array A3 performs better than antenna array A1 and A2. Thus, antenna A4 is the best choice followed by antenna array A3.

Figure 5 shows the percentage available angular region versus SINR threshold level in the presence of three to six interfering signals. All other parameters are the same as in Figure 4. Again, one can see that the percentage available angular region, as expected, decreases with an increase in the number of interfering signals. Also, antenna array A4 performs the best followed by antenna array A3, whereas antenna array A2 has the worst performance. Let us say that for good performance one needs -5 dB or higher output SINR. Then Table 1 shows the available angular region for the four antenna arrays in the presence of three to six CW interfering signals. Note that as the number of interfering signals increases, array configuration A4 performs much better than any other antenna array.

Table 1. Available angular region for the four antenna arrays. SINR threshold = -5 dB.

Number of Interfering Signals	Antenna Array A1	Antenna Array A2	Antenna Array A3	Antenna Array A4
3	82.8%	85.6%	87.6%	88.9%
4	72.5%	73.9%	80.8%	83.9%
5	51.9%	45.9%	69.5%	78.0%
6	10.9%	0.0%	45.0%	70.3%

In the above discussion, the desired signal as well as the interfering signals were assumed to be CW signals. The performance of the antenna arrays in the presence of wideband signals is also of interest for many applications. In the following discussion, the incident signals are assumed to have 2% bandwidth with flat power spectral density. The system (front end) bandwidth is assumed to be 2.5%. All other parameters are the same as before. In the case of wide band incident signals, each incident signal is assumed to consist of many independent narrow band signals centered at different frequencies. The antenna response over the narrow band is assumed to be constant. The covariance matrix for each narrow band signal is calculated. The covariance matrix for a given incident signal is then obtained by adding the various narrow band covariance matrices.

Figures 6 and 7 show the performance of the four antenna arrays in the presence of three to six wide band interfering signals. The desired signal is also assumed to be a wide band signal. All other parameters are the same as in Figures 4 and 5, respectively. Comparing the performance of the four antenna arrays in the presence of wide band signals (Figures 6 and 7) with the performance in the presence of CW signals (Figures 4 and 5), one can see that the performance, as expected, further degrades in the presence of wide band interfering signals. In the absence of all interfering signals (though not shown here), the performance of the four antenna arrays is identical to their performance for CW desired signals. Again antenna array A4 performs the best followed by antenna array A3. Thus antenna array A4 seems to be the best choice.

IV. 7-tap STAP

For wide band incident signals, STAP based antenna electronics is generally used for improved performance. In this section, the performance of the four antenna arrays with 7-tap STAP is discussed. The delay between various taps is selected to be equal to $1/B$, where B is the system bandwidth. Thus, thermal noise between various taps is assumed to be uncorrelated. The STAP weights are also adapted for beam forming/null steering.

Figures 8 and 9 show the performance of the four antenna arrays with 7-tap STAP in the presence of three to six wide band interfering signals. Again, the desired signal is also assumed to be a wide band (2% bandwidth) signal. All other parameters are the same as in Figures 6 and 7, respectively. Comparing the performance in these two sets of figures (Figures 8 and 9, and Figures 6 and 7), one can see that 7-tap STAP, as expected, performs much better than space-only processing. Again, antenna array A4 performs much better than the other antenna arrays. In the presence of five or six interfering signals, the performance difference between various antenna arrays is so significant that one can hardly ignore the antenna element distribution. For the best performance, antenna array A4 is recommended followed by antenna array A3.

If one compares the performance of 7-tap STAP in the presence of wide band signals (Figure 8 and 9) with that of space-only processing in the presence of CW signals (Figures 4 and 5), one will notice that the two are identical. Thus, to find the optimum element distribution, one does not have to worry about wide band signals and/or STAP based antenna electronics. As long as there are enough taps in STAP, wide band signals can be easily handled by STAP and the performance of STAP in the presence of wide band signals will be identical to that of space-only processing in the presence of narrow band (CW) signals. This is a significant observation in that one can reduce the design time for the antenna array by orders of magnitude. Not only one can ignore STAP in the antenna array design process, one does not have to analyze/measure the *in situ* response of various antenna elements over the whole bandwidth of the desired signal. The response at the carrier frequency will be sufficient.

V. Summary and Conclusions

In this paper, the performance of circular adaptive antenna arrays in the presence of multiple interfering signals has been studied. The radius of the antenna array was selected to be half a wavelength and the number of antenna elements was fixed at seven. The individual antenna elements were biconical antennas oriented perpendicular to the plane of the antenna array. It was shown that the element distribution significantly affects the performance of the antenna array in adaptive mode. This is especially true when the total number of interfering signals reaches the antenna degrees of freedom. For the best performance, the antenna elements should be distributed on the perimeter of the array aperture. If the application requires that one of the antenna elements be at the center of the circular aperture, then the rest of the antenna elements should be distributed non-uniformly on the perimeter of the circular aperture. One good arrangement is antenna array configuration A3 studied in this paper.

Another interesting observation made in this paper is that the performance of space-only processing in the presence of CW signals is identical to the performance of 7-tap STAP in the presence of wide band signals. Thus, while investigating various antenna element distributions for adaptive antenna arrays, one can work with CW incident signals and space-only processing. This should significantly reduce the effort involved in the investigation.

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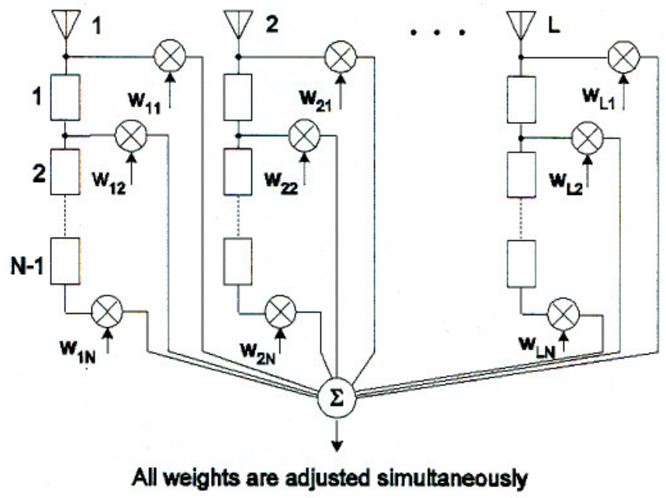

Figure 1. A block diagram of STAP based adaptive arrays, Delay between taps = T_0.

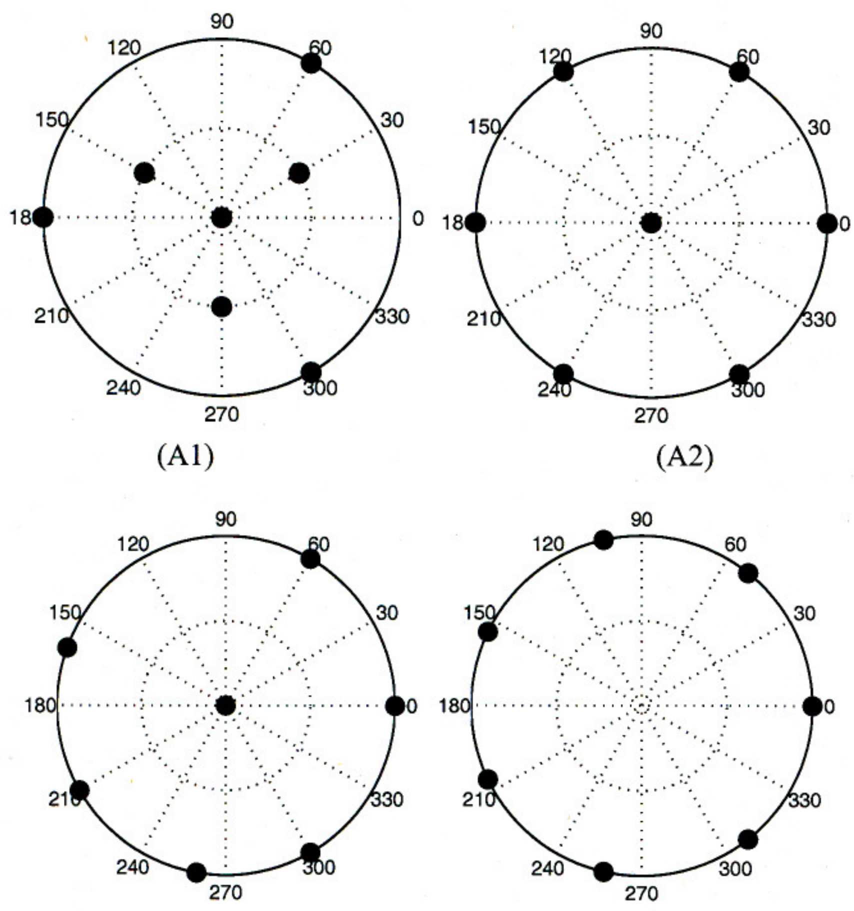

Figure 2. Various distributions of antenna elements.

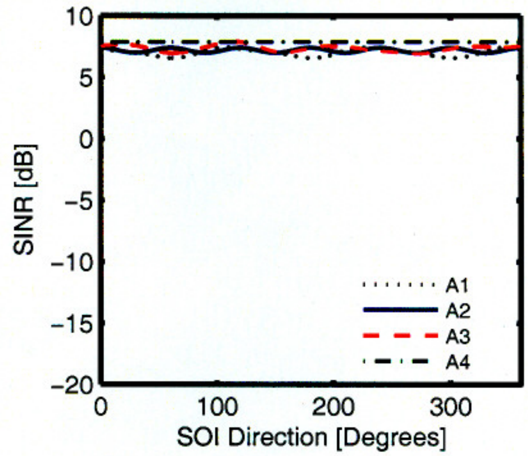

Figure 3. Output SINR versus the desired signal direction in the absence of all interfering signals.

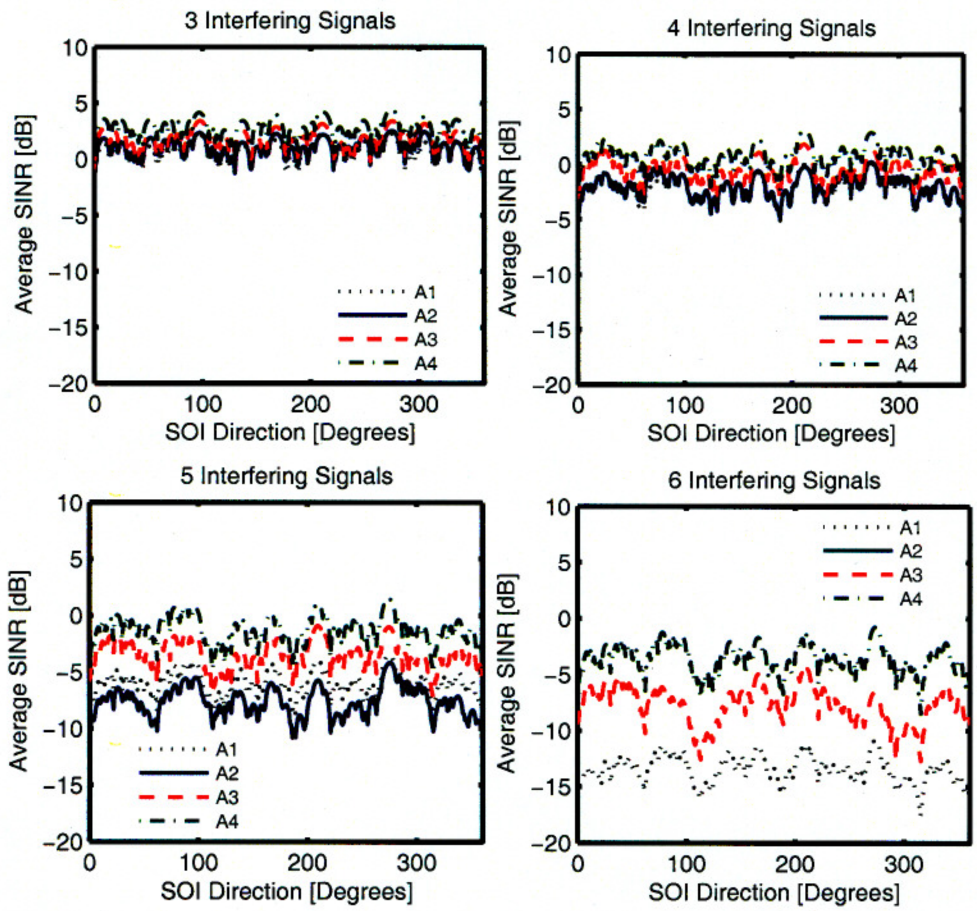

Figure 4. Average output SINR versus the desired signal (SOI) direction in the presence of three to six interfering signals. CW signals, space-only processing.

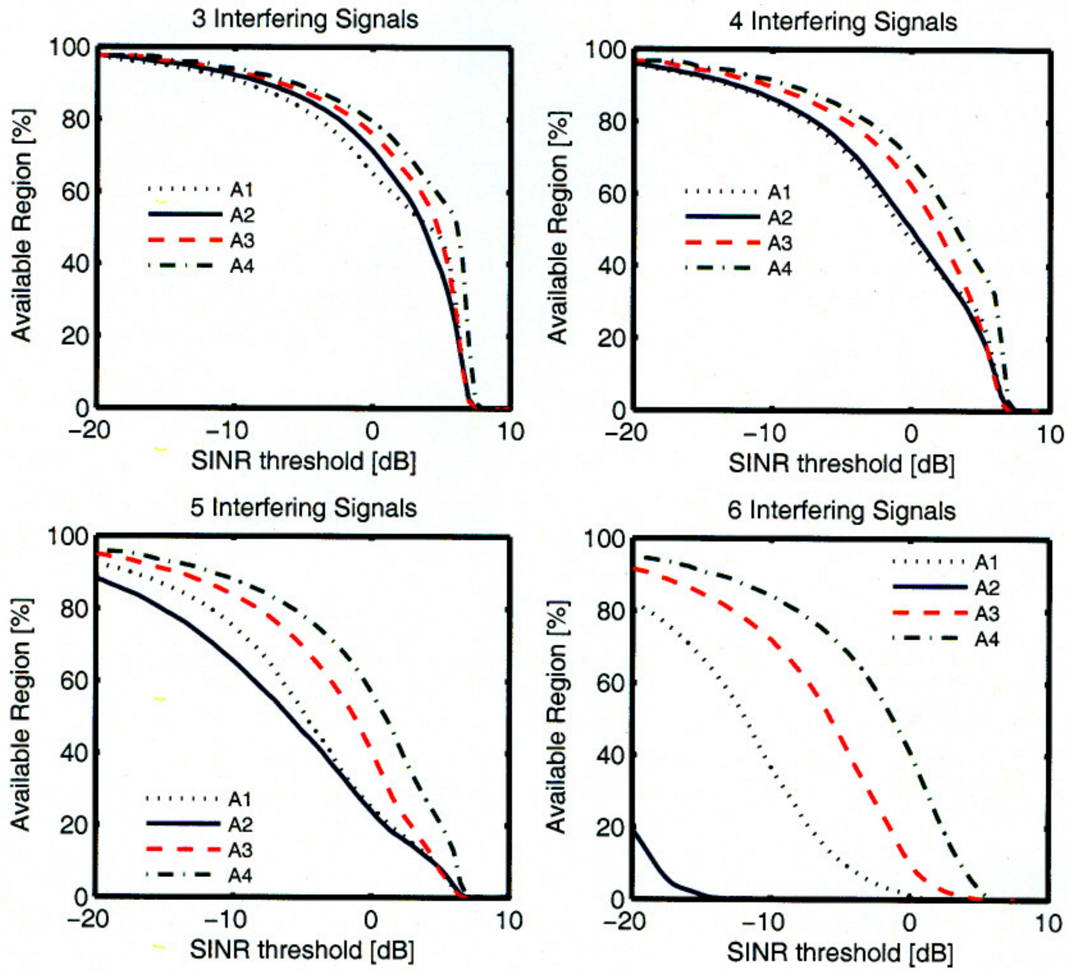

Figure 5. Available angular region versus SINR threshold in the presence of three to six interfering signals. CW signals, space-only processing.

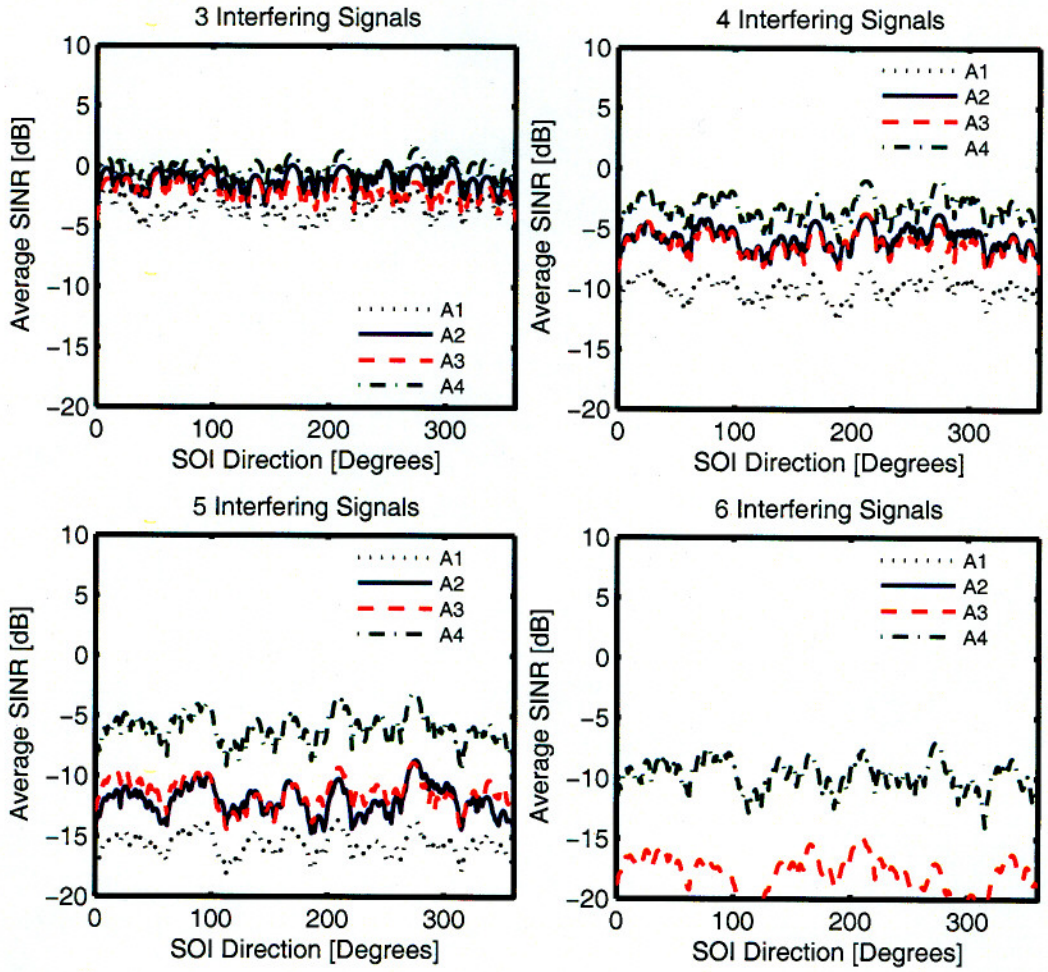

Figure 6. Average output SINR versus the desired signal (SOI) direction in the presence of three to six interfering signals. Wide band signals, space-only processing.

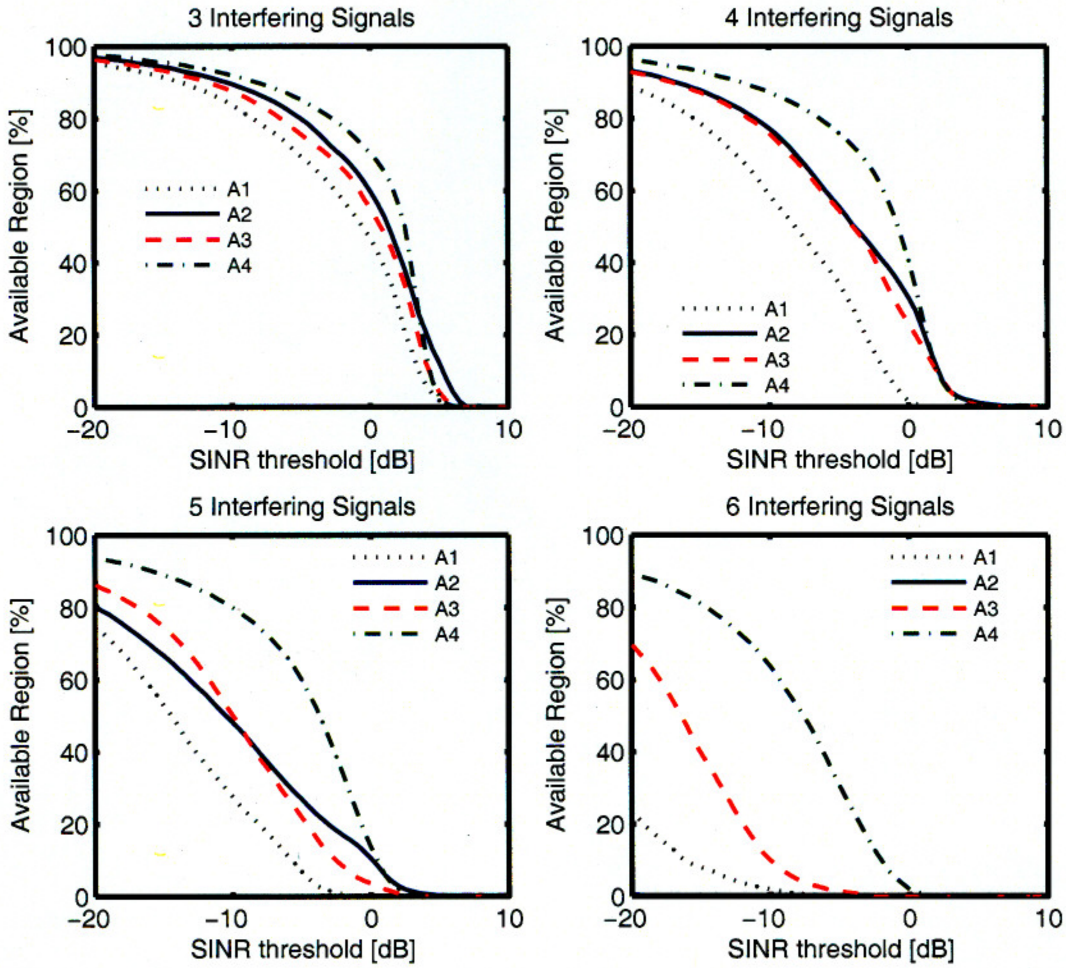

Figure 7. Available angular region versus SINR threshold in the presence of three to six interfering signals. Wide band signals, space-only processing.

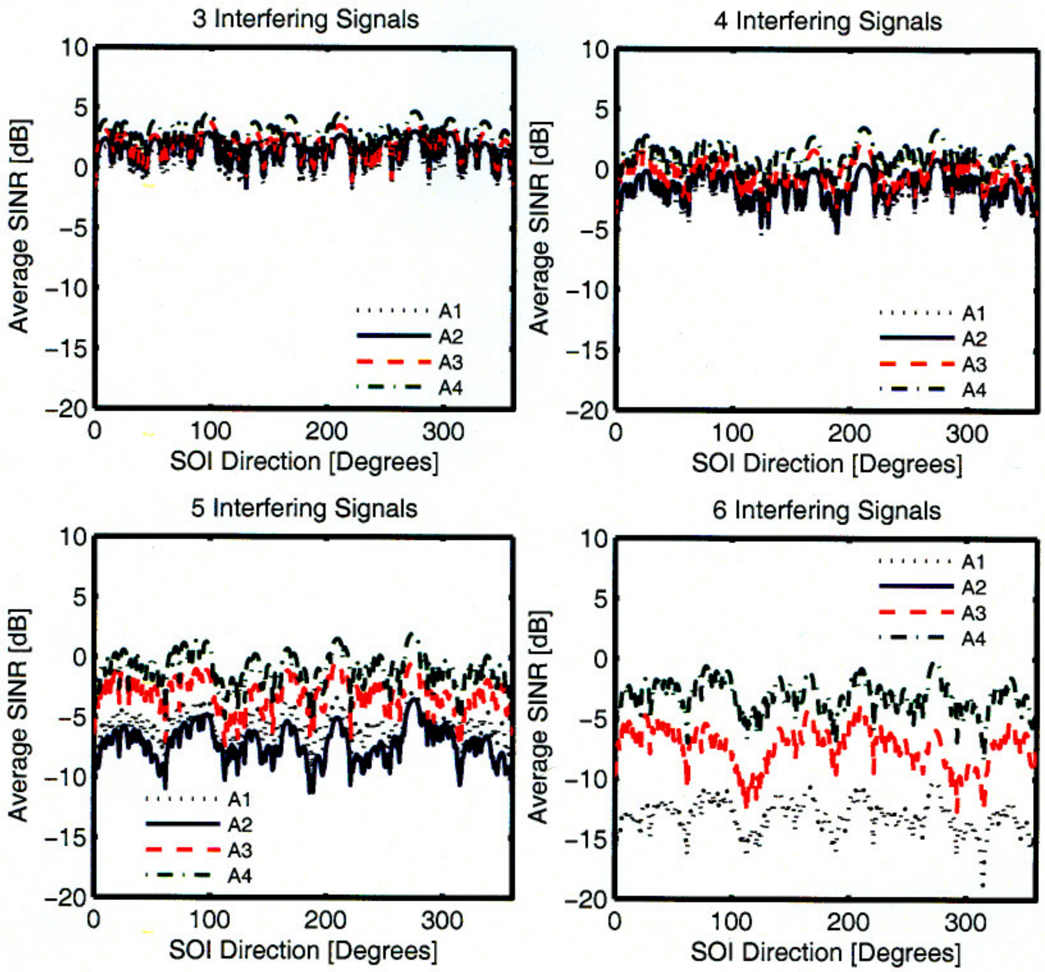

Figure 8. Average output SINR versus the desired signals (SOI) direction in the presence of three to six interfering signals. Wide band signals, 7-tap STAP.

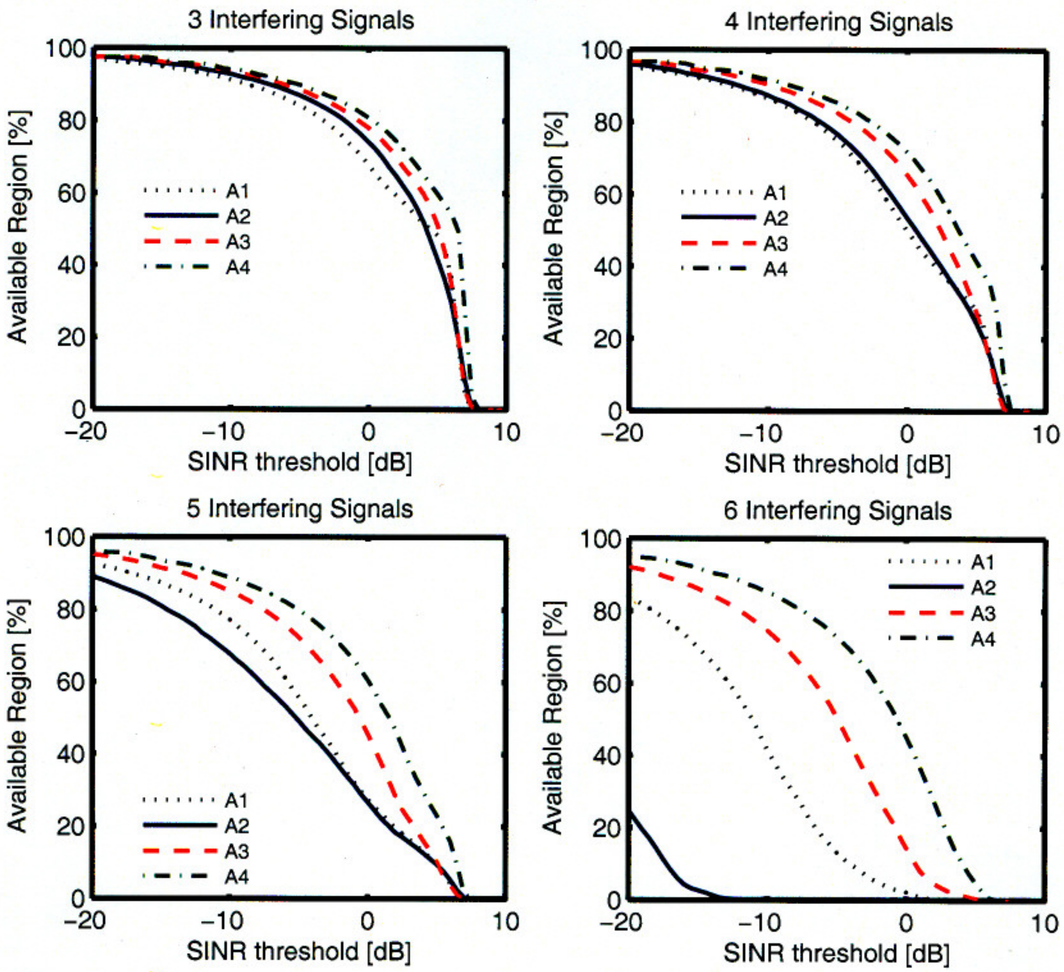

Figure 9. Available angular region versus SINR threshold in the presence of three to six interfering signals. Wide band signals, 7-tap STAP.

GPS Antenna Working Group (AWG)
The MITRE Corporation, Bedford, MA
9 November 2005

0800-0830	DRM	Lt Luna
0830-0900	Rotor Modulation	MITRE
0900-0930	SAS/Rotor Modulation Discussion	SQNLDR Durant/Lt Hogan/MITRE
0930-0945	Break	
0945-1005	Antenna Gain Coverage Calculations	Paul Rousseau
1005-1025	Three Antennas Group Delay Calibration	Paul Rousseau
1025-1040	Break	
1040-1100	Antenna Gain Coverage Calculation	Paul Rousseau
1100-1120	MEMS IMU/S-CRPA Integration	Bob Yang
1120-1150	Multi Beam AE Electronics & Legacy GPS Receivers	Dr. Jiti Gupta
1150-1300	Lunch	
1300-1330	Digital Unloading in AE for Weak Interfacing Signals	Dr. Jiti Gupta
1330-1415	Performance of Stap Based GPS AE in Overstressed Jamming Scenarios	Dr. Jiti Gupta
1415-1430	Break	
1430-1510	ADAP Vulnerability Jamming Test Design	MITRE
1510-1550	Coherent Receiver Process	MITRE
1150-1605	Break	
1605-1645	Insights into STAP Process	MITRE